Method of processing seismic data acquired by means of multicomponent sensors

GENERAL FIELD

The invention relates to techniques for processing seismic data acquired by means of multicomponent sensors.

This invention is in particular applicable to acquisition by means of cables disposed on the bottom of the sea (so-called "OBC" or "Ocean Bottom Cable" techniques).

Multicomponent geophones capable of working in any position whatsoever, in particular at the bottom of the sea, have recently been proposed. This "omnitilt" probe technology has allowed new simplified cables (mechanical joints are no longer necessary) and allows acquisitions with a better seismic bandwidth.

However, the acquisition step does not make it possible to provide the true orientation of the geophones of the cable, although this information is indispensable for making it possible to process the data.

The invention proposes a processing which is intended to be implemented on raw data and which allows reorientation and calibration (intended to convert the measurements of various geophones into a common phase and amplitude response).

STATE OF THE ART

Techniques consisting in isolating from the signal the data which correspond to the first arrival at the sensor and in determining on the basis of these data a filter intended to be applied to the raw data so as to correct them and to thus obtain the components of the signal on the expected axes have already been proposed.

A proposal to this effect has been described in the article:
"Horizontal vector infidelity correction by general linear transformation" - Joe Dellinger et al. - SEG - 9-14 September 2001.

However, this technique is not necessarily optimal since the coupling mechanism which intervenes at the geophone level is not the same for the waves which correspond to a first arrival at the sensor and for the waves reflected or converted by the seismic horizons.

PRESENTATION OF THE INVENTION

The invention proposes another approach which employs the true data window for numerically reconstructing geophones oriented along the desired axes.

Implicitly, this approach compensates for the errors which are not related to the geophones themselves, but which are due to the fact that the coupling between the geophone and the waves to be recorded is different depending on whether it is necessary to make a vertical vibration movement rather than a horizontal movement (on account of gravity).

In the case of a cable, the coupling is furthermore different depending on whether the vibration movement is in the direction of the cable or transverse.

Moreover, since deeper windows are subject to a lower S/N (signal-to-noise) ratio, processing which implements trace stacks is moreover used.

The invention thus proposes, according to a first aspect, a method of processing seismic data acquired by means of a sensor having at least three geophone components, characterized in that estimators are

determined which are combinations of these components making it possible to isolate the various data depending on whether they correspond to propagation with reflection or with conversion and in that, to determine a sensor reconstruction, the operators to be applied to the various components of the sensor are determined in such a way as to minimize the deviation between reference data and data obtained by applying the estimators to the sensor reconstruction, the operators thus determined being applied to the data acquired.

It is specified here that, in the remainder of the present text, the term geophone is understood to mean any velocity sensor and the term hydrophone any pressure sensor.

Preferred, but non limiting aspects of the method according to the first aspect of the invention are the following:

- the sensor furthermore including a hydrophone, the reference data for reconstructing a vertical geophone are derived from the data acquired by the hydrophone;
- the reference data for reconstructing a vertical geophone without hydrophone or for reconstructing horizontal geophones are derived from the application of the estimators to one of the geophones of the sensor;
- the orientation in the horizontal plane of a geophone component is obtained by minimizing the estimator of the transverse reflection;
- the estimators are determined as a function of a model of isotropic propagation or including the azimuthal anisotropy.

According to another more general aspect, the invention proposes a method of processing seismic data acquired by means of a sensor having at least three geophone components, characterized in that estimators are

determined which are combinations of these components making it possible to isolate the various data depending on whether they correspond to propagation with reflection or with conversion. The estimators thus determined may find applications other than that forming the subject of the method according to the first aspect of the invention.

DESCRIPTION OF THE FIGURES

- Figure 1 is a diagrammatic representation giving the angular conventions used;
- Figures 2 and 3 are flow charts giving the various steps of the processing respectively in one and the other of the two exemplary implementations described.

DESCRIPTION OF ONE OR MORE MODES OF IMPLEMENTATION OF THE INVENTION

First exemplary implementation: case of an isotropic propagation model

Under the assumption of a locally 1D (one dimensional) geology in proximity to the receivers, and assuming isotropic propagation of the earth, a given geophone, with an orientation ϕ ψ, measures:

$$m_k = Rpp\ \cos(\psi)\delta pp_k + (Rps\ \cos(\theta_k - \phi) + Rtrsv\ \sin(\theta_k - \phi))\sin(\psi)\delta ps_k$$

With :

k : index for the shotpoint (from 1 to N)

θ_k : azimuth of the shotpoint with respect to the abscissa axis

$-R_{pp}$: reflectivity PP

δ_{pp} : dynamic correction PP ("normal moveout" or NMO)

Rps : isotropic radial reflectivity PS

Rtrsv : isotropic transverse reflectivity PS

δ_{Ps} : dynamic correction PS ("normal moveout" or NMO)

This model allows the evaluation of the reflectivity parameters from the set of traces tr_k through simple processing of least squares comparison (ignoring ψ to begin with) in the Fourier domain, leading to the following equations:

$$\begin{pmatrix} \frac{N}{wc(\varphi)} & wc(\varphi) & ws(\varphi) \\ & Sc2(\varphi) & Scs(\varphi) \\ ws(\varphi) & Scs(\varphi) & Ss2(\varphi) \end{pmatrix} \cdot \begin{pmatrix} Rpp \\ Rps \\ Rtrsv \end{pmatrix} = \begin{pmatrix} Svx \\ Shcx(\varphi) \\ Shsx(\varphi) \end{pmatrix}$$

<u>Scalar quantities</u>:

$Sc(\phi) = \Sigma_k \cos(\theta_k-\phi)$ $Ss(\phi) = \Sigma_k \sin(\theta_k-\phi)$

$Sc2(\phi) = \Sigma_k \cos^2(\theta_k-\phi)$ $Ss2(\phi) = \Sigma_k \sin^2(\theta_k-\phi)$

$Scs(\phi) = \Sigma_k \cos(\theta_k-\phi) \sin(\theta_k-\phi)$

$N = Sc2 + Ss2$

<u>Wavelet quantities</u>:

$wc(\phi) = \Sigma_k \cos(\theta_k-\phi)\delta ps_k\ \delta pp_k^{-1}$

$ws(\phi) = \Sigma_k \sin(\theta_k-\phi)\delta ps_k\ \delta pp_k^{-1}$

<u>Trace stack quantities for geophone x</u>:

$Svx = \Sigma_k x_k \delta pp_k^{-1}$

$Shcx(\phi) = \Sigma_k \cos(\theta_k-\phi)\ x_k \delta ps_k^{-1}$

$Shsx(\phi) = \Sigma_k \sin(\theta_k-\phi)\ x_k \delta ps_k^{-1}$

The solution of this linear system gives:

$\Delta iso\ Rpp \cos(\psi) = W\ Svx + (Scs\ ws-Ss2\ wc)Shcx + (Scs\ wc-Sc2\ ws)Shsx$

$\Delta iso\ Rps \sin(\psi) = Kis \cos(\phi) - Kic \sin(\phi)$

$$\Delta iso\ Rtrsv\ \sin(\psi) = Kis\ \cos(\phi) - Kic\ \sin(\phi)$$

With:

$$W = Sc2\ Ss2 - Scs^2$$

$$\Delta iso = WN + wc(Scs\overline{ws} - Ss2\,\overline{wc}) + ws(Scs\overline{wc} - Sc2\overline{ws})$$

$$Kic = (Scs\,\overline{ws} - Ss2\,\overline{wc})Svx + (N\,Ss2 - ws\,\overline{ws})Shcx + (-N\,Scs + ws\,\overline{wc})Shsx$$

$$Kis = (Scs\,\overline{wc} - Sc2\,\overline{ws})Svx + (-N\,Scs + wc\,\overline{ws})Shcx + (N\,Sc2 - wc\,\overline{wc})Shsx$$

This modelling allows evaluations taking account of the following properties:

a. Rpp does not depend on ϕ,

b. $|Rps|^2+|Rtrsv|^2$ does not of course depend on ϕ either,

c. Δiso is in practice rapidly steady over time and can be ignored for the calibration/orientation procedure, since it is common to all the geophones of one and the same receiver.

Evaluations of dense shots

Most of the OBC acquisitions are gleaned using a dense and regular grid of sources, which allows considerable simplification:

Sc = Ss = 0, wc = ws=0 (symmetry of the sources with respect to the receivers)

Scs = 0 Sc2 = Ss2 = N/2 (isotropic source distribution)

Next, the exact solution can be obtained through the approximation:

$$N\ Rpp\ \cos(\psi) = Svx$$

$$N\ Rps\ \sin(\psi) = 2\ Shcx(\phi)$$

$$N\ Rtrsv\ \sin(\psi) = 2\ Shsx(\phi)$$

This approximation leads to very simple calculations, not involving any wavelets, and can be applied immediately.

Orientation of the geophones

Since Rtrsv does not exist physically, the minimization of the energy of Rtrsv leads to a trigonometric equation which gives the true orientation $\phi_{geo}(+k\ \pi)$:

$$\tan(2\ \phi_{geo}) = 2\ (\sum_i Kic_i\ Kis_i)/(\sum_i Kic_i^2 - \sum_i Kis_i^2)$$

$((Emax-Emin)/(Emax+Emin))^{1/2}$ gives a check on the quality of the reorientation.

Moreover, if one wishes to find the orientation according to the first arrivals, it is possible to correct the said first arrivals so as to set them to one and the same arrival time, then to simplify kic and kis by replacing the wavelets wc and ws by the scalars sc and ss, by considering that the waves recorded horizontally are in fact the projection of the radial wave P, present on all the geophones since it is oblique.

<u>Geophone vertical composite calibration</u>:

With the geophones g_1, g_2, g_3, we construct a vertical composite geophone v, $v = op_1*g_1 + op_2*g_2 + op_3*g_3$ (or comprising additional similar terms in the case where extra geophones are present in the receiver) where op_1, op_2, op_3 are the filters of finite length and op_u*g_u represents the convolution of geophone g_u with filter op_u.

such that:

$$E1 = |XH - XV|^2 = |Kic(v)|^2 + |Kis(v)|^2$$

The energy of the difference between XH (hydrophone after application of the geophone phantom, or cross-ghost hydrophone) and XV (the vertical composite geophone after application of the hydrophone phantom or

cross-ghost geophone), (see for example in this regard the Applicant's Patent Application FR 2 743 896).

$E2 = |Rps(v)|^2 + |Rtrsv(v)|^2$
horizontal energy of the vertical composite,

$E = \lambda E1 + (1-\lambda)E2$ is a quadratic form in the coefficients of the filters and can be reduced to the minimum, thus giving a linear system to be solved. (λ is a matching parameter, $0<=\lambda<=1$, which favours either a greater adjustment to the reference hydrophone or a greater minimization of the shear energy).

In the case of terrestrial data, that is to say if there is no hydrophone available, it is possible to choose one of the geophones as reference and to replace the hydrophone by $Rpp(g_{ref})$.

Calibration in a horizontal arbitrary direction

With $g = op_1*g_1 + op_2*g_2 + op_3*g_3$ and φ_g an arbitrary direction,
We define:
$E1 = |Rps(g, \varphi_g) - Rps(ref, \varphi_{ref})|^2$,
as being the energy of the difference between the evaluation of Rps of the arbitrary composite geophone and the evaluation of Rps of a reference geophone (in general the geophone oriented in the direction of the cable).

$E2 = |Rpp(g)|^2 + |Rtrsv(g, \varphi_g)|^2$ (the nonradial energy)

$E = \lambda E1 + (1 - \lambda)E2$ allows the derivation of a composite horizontal geophone in the desired direction, having the same frequency response as the reference geophone, and with a minimum PP contamination.

Considering the cases $\varphi_{ref} = 0$ and $\varphi_{ref} = \pi/2$, it is possible by simple trigonometric combination to generate the radial and transverse projections.

Second exemplary implementation: case of anisotropic azimuthal propagation modelling

Let α be the direction of the natural fast propagation axis. The modelling of the measurement of the geophone becomes (using one or other of Rps1 and Rps2 the two images along the natural directions, or Rps and δRps defined by Rps1 = Rps + δRps, Rps2 = Rps - δRps):

$$m_k = Rpp\ \cos(\psi)\delta pp_k + (Rps1\ \cos(\varphi-\alpha)\cos(\theta_k-\alpha) + Rps2\ \sin(\varphi-\alpha)\sin(\theta_k-\alpha))\sin(\psi)\delta ps_k$$

$$m_k = Rpp\ \cos(\psi)\delta pp_k + (Rps\ \cos(\theta_k-\varphi) + \delta Rps\ \cos(\theta_k+\varphi-2\alpha))\sin(\psi)\delta ps^k$$

giving the normal equations

$$M = \begin{pmatrix} N & wc(\varphi) & wc(2\alpha-\varphi) \\ \overline{wc(\varphi)} & Sc2(\varphi) & Sc2(\alpha)-N\sin^2(\alpha-\varphi) \\ \overline{ws(2\alpha-\varphi)} & Sc2(\alpha)-N\sin^2(\alpha-\varphi) & Sc2(2\alpha-\varphi) \end{pmatrix}$$

$$M.\begin{pmatrix} Rpp \\ Rps \\ \delta Rps \end{pmatrix} = \begin{pmatrix} Svx \\ Shcx(\varphi) \\ Shcx(2\alpha-\varphi) \end{pmatrix}$$

The solution of this linear system gives:

$$\Delta iso\ Rpp\ \cos(\psi) = unchanged$$

$$\Delta aniso\ Rps\ \sin(\psi) = (Kac\ \cos(2\alpha-\varphi) + Kas\ \sin(2\alpha-\varphi))\sin(2(\alpha-\varphi))$$

$$\Delta aniso\ Rtrsv\ \sin(\psi) = (-Kac\ \cos(\varphi)-Kas\ \sin(\varphi))\sin(2(\alpha-\varphi))$$

With:

$\Delta aniso = \sin^2(2(\alpha-\varphi))\Delta iso$
$Kac = (Sc2\,\overline{ws} - Scs\,\overline{wc})Svx + (N\ Scs - wc\,\overline{ws})Shcx - (N\ Sc2 - wc\,\overline{wc})Shsx$
$Kas = (-Ss2\,\overline{wc} + Scs\,\overline{ws})Svx + (N\ Ss2 - ws\,\overline{ws})Shcx - (N\ Scs - ws\,\overline{wc})Shsx$

Vertical calibration of composite geophone:

The isotropic process remains applicable with the change

$$E2 = |Kac(g)|^2 + |Kas(g)|^2$$

Horizontal arbitrary calibration or rows/columns of composite geophones

The observation of δRps over the data field makes it possible to diagnose the presence (or otherwise) of significant azimuthal anisotropy. (the quantity $\sin^2(2(\alpha-\varphi))\delta Rps$ does not require a knowledge of α for its calculation).

The isotropic process remains applicable with the changes

$$E2 = |\delta Rps(v)|^2 \text{ and } E = \lambda(E1+E2)+(1-\lambda)E3.$$

When α is not generally known, a scan over a range of π/2 is implemented, using the value of α which minimizes Emini/E0.